ICON – MPI – DWD

Icosahedral GCMs for climate research and operational weather forecasting

DWD: Günther Zängl, Daniel Reinert, et al.

MPI-M: Marco Giorgetta, Levy Silvers et al.

Former: Luca Bonaventura, Almut Gassmann, Hui Wan

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Original motivation, ca. 2001

- MPI-M and DWD models are not satisfactory for future needs:

- MPI-M uses ECHAM/MPIOM as coupled climate model
  - ECHAM breaks tracer wind consistency due to a mix of spectral transform method for equations of motion and flux form semi-Lagrange transport scheme for tracers
  - ECHAM is hydrostatic → no option for cloud modelling
  - Scaling issues

- DWD uses global GME and regional COSMO for weather forecasting
  - Difficulties resulting from the usage of different dyn. equations,grids, numerics and parameterizations
  - No ocean model available for seasonal or decadal prediction

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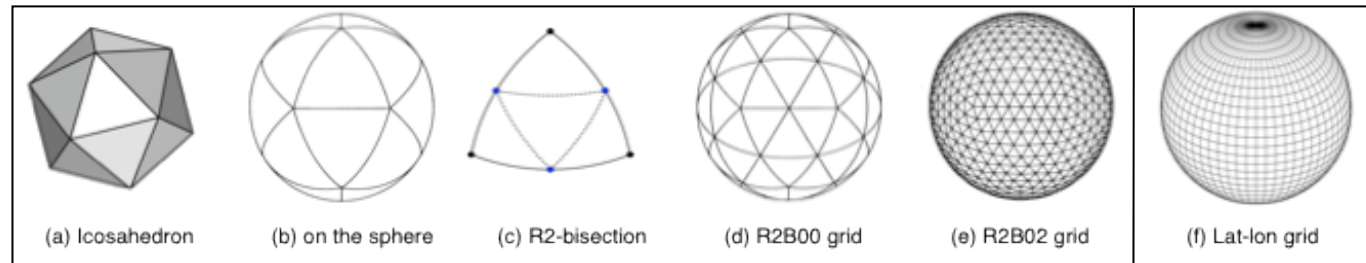
Goals and scope for new model

- Unified usage as climate model and NWP model to link daily verification of NWP to longer time scales
  - Atmospheric dynamical core must be fit for resolutions from ~1 to ~100 km and vertical extent to ~80 km
  - Tracer wind consistency
  - Regional refinement for simultaneous global and regional forecasting
  - Scale related physics packages (or scale aware physics?)
- High numerical efficiency and scalability:
  - Weak and strong scalability for NWP and climate
  - Usage on massively parallel machines (O(4+) cores)
- Framework for the development of atmosphere, land and ocean
  - Common infrastructure
  - Common grids

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ICON characteristics

- Fully compressible equations of motion

- Mass and tracer mass conservation

- Icosahedral grids to avoid polar singularities and obtain a relatively uniform horizontal resolution
    - Option for triangle or hexagon/pentagon grids

- Static grid refinement by one–way or two-way grid nesting in 1 or several regions with individual refinement
    - Unstructured grid
    - Triangles allow simple refinement procedure

- Fast numerics that scales well and may be used with GPUs etc.
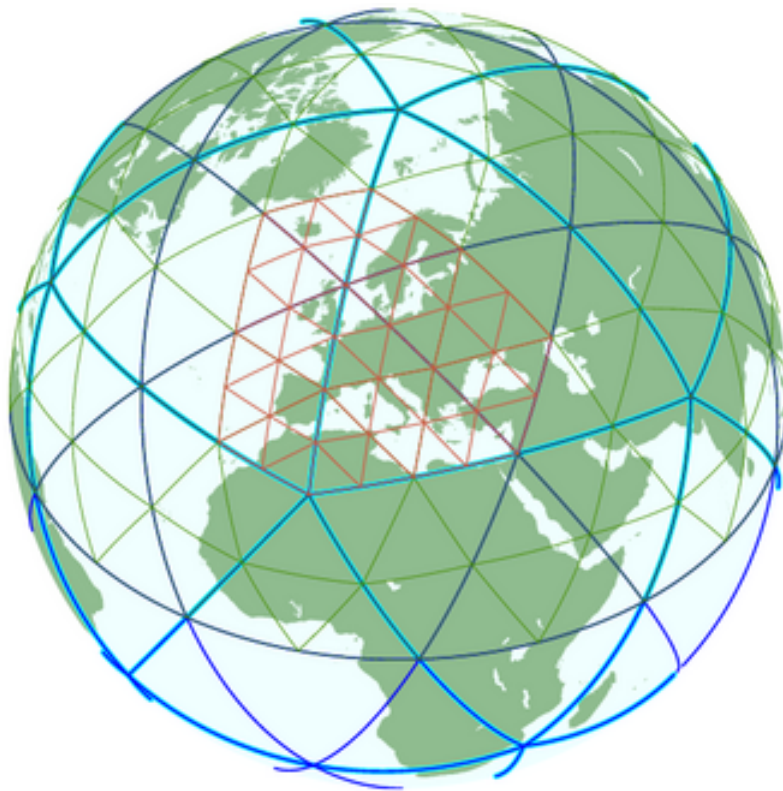   - Small stencils
    - No global communication

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Grid construction

(a) Icosahedron   (b) on the sphere   (c) R2-bisection   (d) R2B00 grid   (e) R2B02 grid   (f) Lat-lon grid

(a) → (b)   Project the icosahedron into the sphere

(c) and (d) Root refinement: Partition each edge into m sections of equal length and connect these points with great circle arcs parallel to the edges → "Rm"

(e)   Further global refinements: Make bisection of edges and connect by great circle arcs, repeat n times → "Bn"

    Regional refinement: As for global, but limited to a region

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Grid examples

- Light blue: spherical icosahedron (R1B0)
- Dark blue: global R2B0
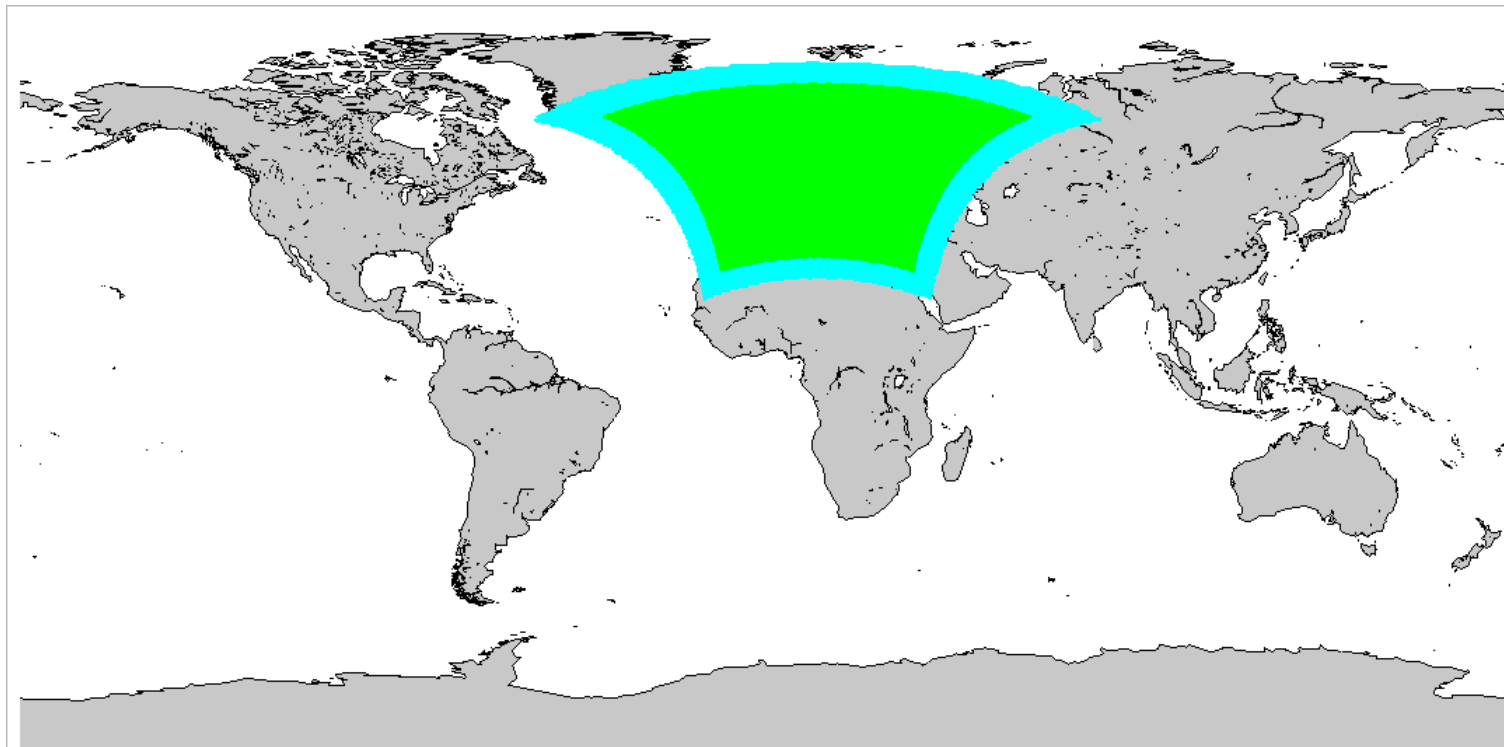- Green: Northern hemisphere R2B1
- Red: Europe R2B2
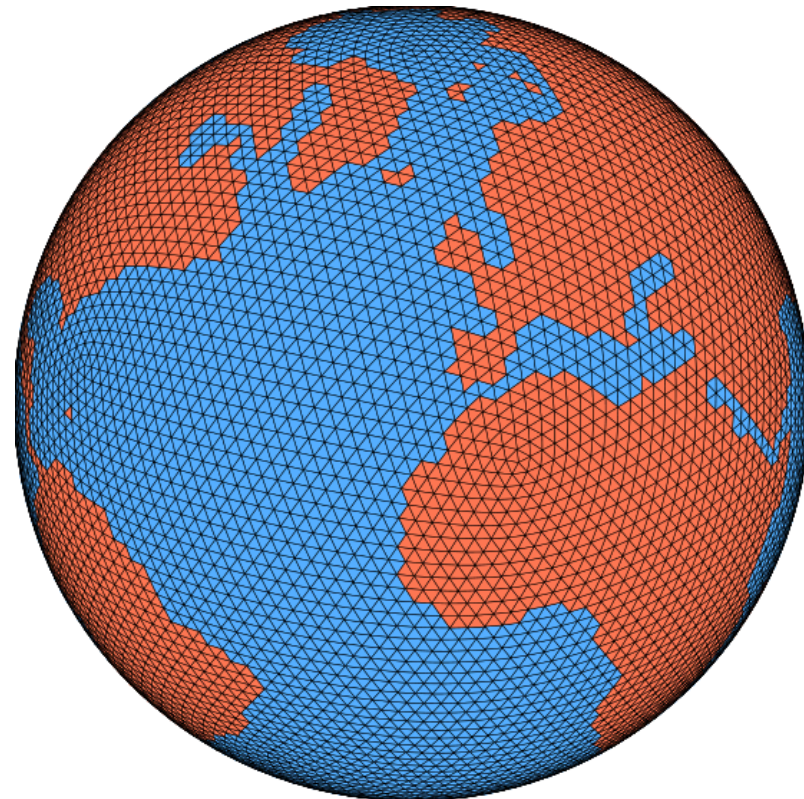
- Land sea mask at R2B4 (~140 km)
- Ocean cells have 2 wet edges
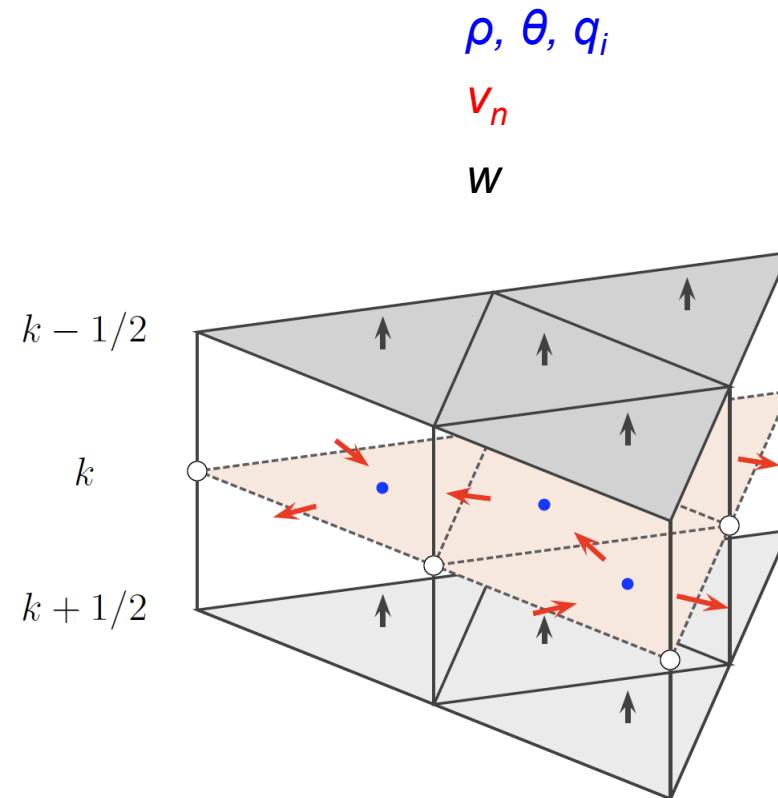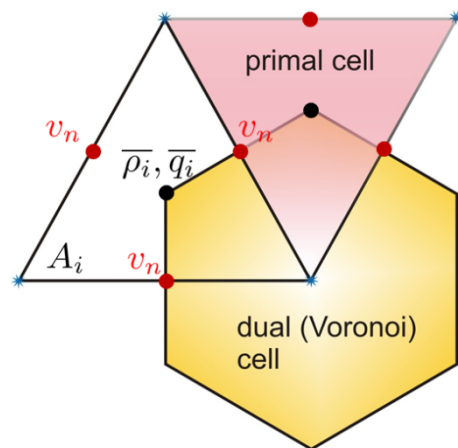- Additional manipulation required for straits, passages etc.

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Prototype grid setup at DWD

- Global R2B7 (~20 km)
- 2 fold refinement over Europe (~5 km)

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Staggering of variables

- C – grid staggering in horizontal and Lorenz grid in vertical:

ρ, θ, q_i

v_n

w

Basic operators on triangular grid

1. **Divergence**
   Gauss's theorem
   (problematic)
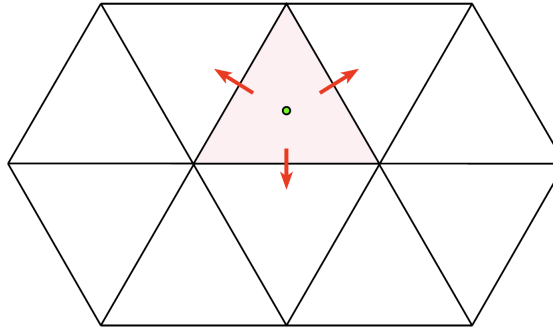
2. **Gradient**
   finite difference

3. **Curl**
   Stokes' theorem

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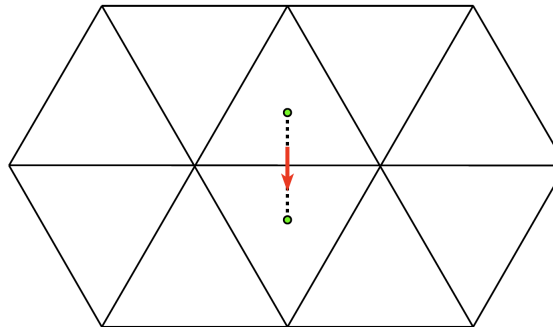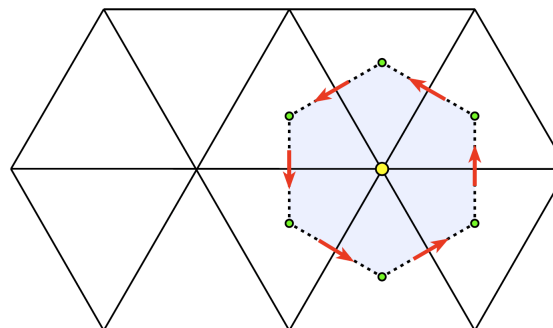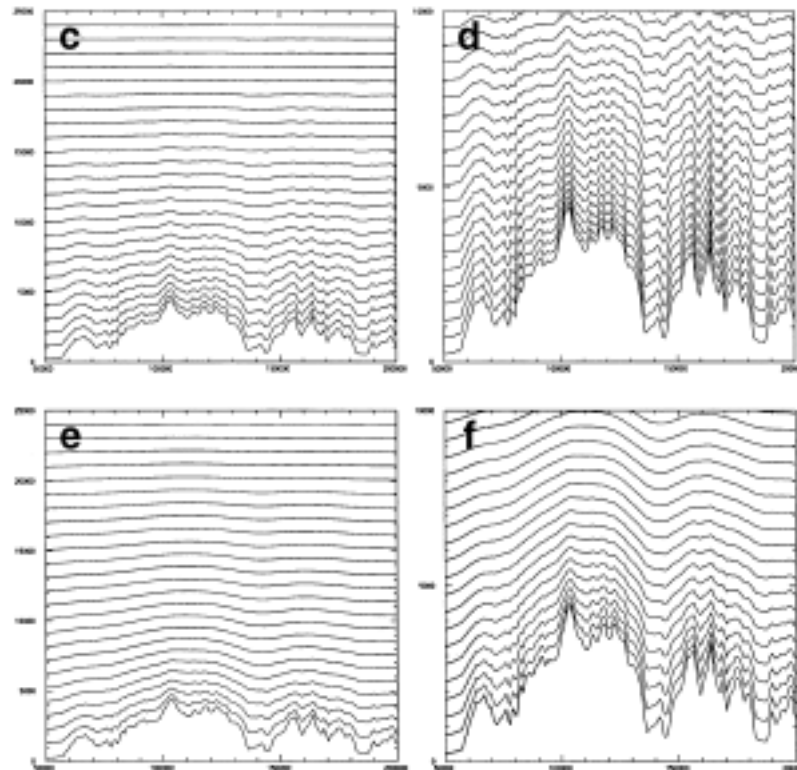
Vertical grid

- **Hybrid sigma height grid**

  – **Without or**

  – **or with smoothing with altitude (Schär et al., 2002)**

(Fig. from Schär et al., 2002)

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Fully compressible system of equations
(shallow atmosphere apr., spherical Earth, constant gravity)

$$\frac{\partial v_n}{\partial t} + (\zeta + f)v_t + \frac{\partial K}{\partial n} + w\frac{\partial v_n}{\partial z} = -c_{pd}\theta_v\frac{\partial \pi}{\partial n}$$

$$\frac{\partial w}{\partial t} + \nabla \cdot (\vec{v}_n w) - w\nabla \cdot \vec{v}_n + w\frac{\partial w}{\partial z} = -c_{pd}\theta_v\frac{\partial \pi}{\partial z} - g$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\vec{v}\rho) = 0$$

$$\frac{\partial \rho\theta_v}{\partial t} + \nabla \cdot (\vec{v}\rho\theta_v) = 0$$

v_n, w: normal/vertical velocity component

ρ: density

θ_v: Virtual potential temperature

K: horizontal kinetic energy

ζ: vertical vorticity component

π: Exner function

blue: independent prognostic variables

Numerical implementation

- 2D Lamb transformation for nonlinear momentum advection

- Flux form for continuity equation and thermodynamic equation; Miura 2nd-order upwind scheme (centered differences) for horizontal (vertical) flux reconstruction

- Finite-volume tracer advection scheme (Miura, 2007) with
    - 2nd-order and 3rd-order accuracy for horizontal advection;
    - 3rd-order piecewise parabolic method for vertical advection
    - monotonous and positive-definite flux limiters

Transport scheme (Miura, 2007)

- Compute flux of tracer mass over each edge from the approximated integrals of the tracer concentration over the departure regions
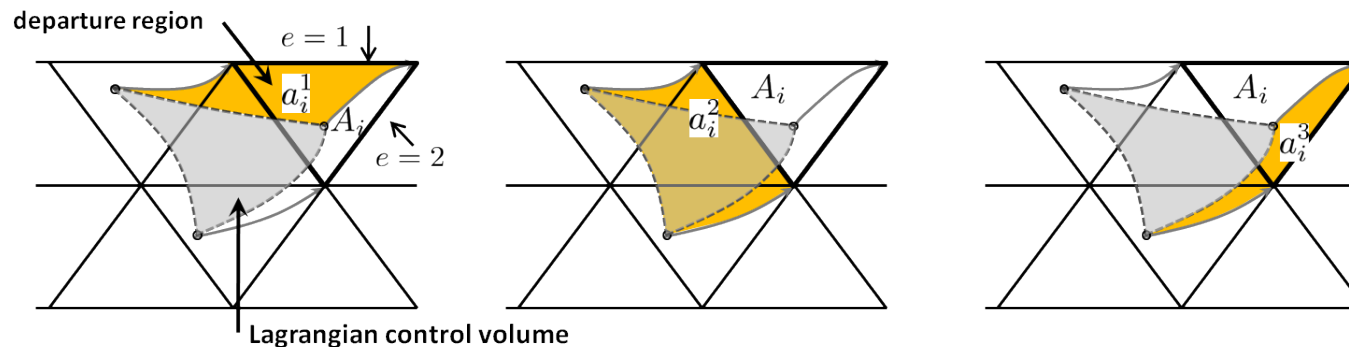
- Rhomboidal approximation of the departure region
- Linear, quadratic or cubic polynomial reconstruction
- Integrate polynomials with Gaussian quadrature (1 or 4 quadrature points).
- Simplified integration: apply polynomial of upwind cell, even if departure region overlaps with several neighboring grid cells
- Use dynamical core mass flux to obtain tracer and air mass consist

Time stepping

- Two time level predictor corrector scheme

- Horizontally explicit time stepping within the dynamical core at the time step needed for sound waves
  - Avoid complications of implicit methods and their risks for scaling properties
  - Efficiency gains of split-explicit time-stepping schemes (based on Leapfrog or Runge-Kutta) are less clear for global models extending to the mesosphere due to smaller ratio between sound speed and maximum wind speed

- Vertically implicit time stepping

- Longer time step for tracer advection and physics schemes

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Process splitting

1. Dynamics with slow physics $n_{now} \rightarrow n_{new}*$ (in m sub steps)
   - Radiation (reduced freq. for rad. transfer, red. resolution)
   - Convection
   - GWD
   - Divergence damping

2. Horizontal diffusion on v_n and θ: $n_{new}* \rightarrow n_{new}*'$

3. Tracer transport: $n_{now} \rightarrow n_{new}*'$
   - Strang or Godunov splitting of horizontal and vertical advection

4. Fast physics, time split $n_{new}*' \rightarrow n_{new}$
   1. Saturation adjustment
   2. Turbulent fluxes
   3. Cloud microphyiscs
   4. Saturation adjustment
   5. Surface/soil processes

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Problems

- Triangular C-grid has computational mode (cf. Dave Randall's talk) triggered by the discretized divergence operator

$$\mathrm{div}\,(\mathbf{v})_i \;=\; (\nabla \cdot \mathbf{v})_o + \boxed{(-1)^{\delta}\, l}\, H(\mathbf{v})_o \;+\; \mathcal{O}\left(l^2\right)$$

- Options:
  1. Suppress the computational mode → ICON-MPI-DWD
     - Divergence damping
     - Filter normal wind used for divergence operator

  2. Use hexagonal instead of triangular C-grid, → ICON-IAP, Gassmann (2012)

  3. Other grid/discretization → cf. variety of DCMIP models
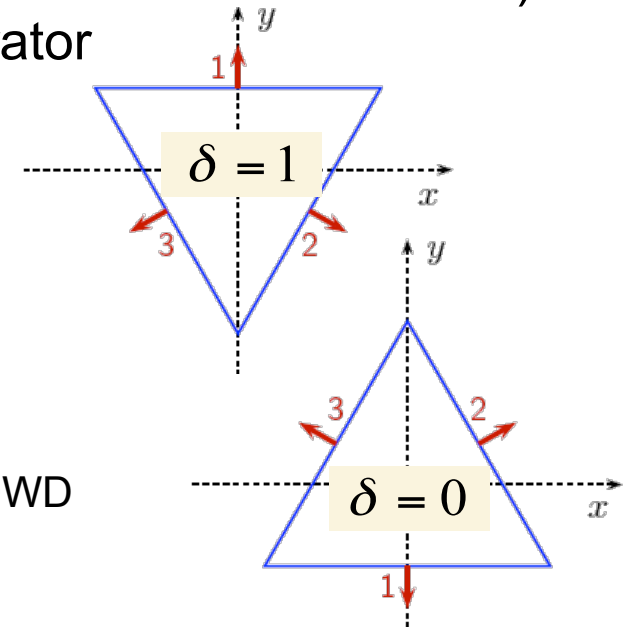
Summary

- The ICON-MPI-DWD model is developed for application over a wide range of scales in space and time

- Non-hydrostatic, fully compressible
- Mass and tracer mass conservation
- Numerical efficiency and high scalability

- Triangular C-grid problems suppressed numerically

- Model is in NWP test mode

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